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Abstract

Sensitive changes in precipitation influence the stability of semiarid ecosystem, rain-fed agriculture, and densely populated society in northern monsoonal China (NC). However, shortage of regional-scale quantitative syntheses imposes restrictions on investigating long-term relationships among precipitation dynamics, possible climatic forces, and prehistoric demographic fluctuations. Herein, we contribute a regionally compiled anomaly record for Holocene annual mean precipitation (PANN) relative to its modern-day values in NC. The Holocene PANN variations in NC may be essentially determined by changing thermal gradients of continental land-ocean and west-east equatorial Pacific, profoundly affecting strength and location of West Pacific Subtropical High that may principally modulate intensity of East Asian summer monsoon and resultant rainfall in NC. Importantly, variation partitioning analysis quantitatively demonstrates that the overall changes of precipitation (43.3%) may play a more important role than temperature (3.2%) and their shared effects (0.8%) in independently accounting for long-term variation of regional-scale Holocene population fluctuations in NC.

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Regional-Scale Precipitation Anomalies in Northern China During the Holocene and Possible Impact on Prehistoric Demographic Changes

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Key Points:
- First, we provide a regionally synthesized quantitative record for Holocene precipitation anomalies over northern China (NC)
- Precipitation dynamics in NC may be essentially related to changing thermal gradients of land-ocean and west-east equatorial Pacific
- Precipitation possibly plays a more important role than temperature in independently affecting long-term prehistoric demographic variations in NC

Supporting Information:
- Supporting Information S1

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Abstract Sensitive changes in precipitation influence the stability of semiarid ecosystem, rain-fed agriculture, and densely populated society in northern monsoonal China (NC). However, shortage of regional-scale quantitative syntheses imposes restrictions on investigating long-term relationships among precipitation dynamics, possible climatic forces, and prehistoric demographic fluctuations. Herein, we contribute a regionally compiled anomaly record for Holocene annual mean precipitation (PANN) relative to its modern-day values in NC. The Holocene PANN variations in NC may be essentially determined by changing thermal gradients of continental land-ocean and west-east equatorial Pacific, profoundly affecting strength and location of West Pacific Subtropical High that may principally modulate intensity of East Asian summer monsoon and resultant rainfall in NC. Importantly, variation partitioning analysis quantitatively demonstrates that the overall changes of precipitation (43.3%) may play a more important role than temperature (3.2%) and their shared effects (0.8%) in independently accounting for long-term variation of regional-scale Holocene population fluctuations in NC.

Plain Language Summary Quantitative inferences of regional-scale precipitation fluctuations on time spans longer than instrumental climatic records are requested to better predict long-term changes of East Asian summer monsoon that influences the lives of nearly one fourth of the total population in our world. Evaluating the possible role of large-scale climatic changes on affecting human population sizes of the distant past is a pressing concern and remains contentious. In this study, for the first time, we provide a regionally synthesized record of Holocene precipitation anomalies relative to present-day values for the monsoon-influenced northern China. This composite record has been demonstrated to be reliable as a representative for reflecting broad-scale precipitation variations across northern China. In addition, we first quantify the relative contribution from both precipitation and temperature on influencing the Holocene demographic changes in northern China. Our results suggest that precipitation may be more important compared with temperature when independently explaining the total variation in long-term prehistoric population patterns.

1. Introduction

Since instrumental climatic data sets cover a few hundred years, quantitative inferences of paleoclimatic parameters in space and time are required for validating climatic model outputs, assessing climatic variability to different forcing mechanisms, and foreseeing future climatic changes (e.g., Braconnot et al., 2012; Renssen et al., 2009). It is therefore increasingly significant to aggregate quantitative paleoclimatic data sets on regional to continental scales for extracting spatially coherent information on past variability of temperature and precipitation all over the world (e.g., Kaufman et al., 2004; Marcott et al., 2013; Marsicek et al., 2018; Seppä et al., 2009). However, there has been a shortage of regional-scale numerical precipitation anomaly of the Holocene relative to the present-day values for the monsoon-influenced region in northern China (NC), where diverse ecosystems, rain-fed farming, and densely populated society are sensitive to variable water supply. So far, several previously synthesized Holocene records with respect to moisture changes on varying spatial scales in NC are limited to qualitative or semiquantitative indexes (e.g., Ran & Feng, 2013; Tian et al., 2016; Wang et al., 2014). Moreover, individual Holocene precipitation reconstructions in NC are restricted to specific sites representative for a small area (e.g., Jiang et al., 2006; Stebich et al., 2015; Xu et al., 2010). In addition, stalagmite $\delta^{18}O$ records in China are often interpreted to reflect broad-scale monsoon precipitation variations (e.g., Wang, Wu et al., 2008; Wang et al., 2001; Zhang et al., 2008). However, recent proxy records and climate modeling results argued that most of the Holocene stalagmite $\delta^{18}O$ sequences from both northern and southern China may be a signal of atmospheric vapor source instead of monsoon precipitation (e.g., Caley et al., 2014; Chen et al., 2014; Liu et al., 2015). Taken together, it is clearly necessary to obtain a regionally compiled precipitation record for NC during the Holocene and to properly evaluate the forcing mechanism.

Numerous modern observations, paleoclimatic syntheses, and modeling efforts point out that large-scale precipitation changes in NC can be regarded as a direct and unequivocal indicator for the strength of East Asian summer monsoon (EASM) compared to other regions in monsoonal China (e.g., Zhou et al., 2009, 2011; Ge et al., 2012; Liu et al., 2014, 2015; Chen, Xu, et al., 2015). The enhancement of EASM intensity is typically characterized by an increased annual rainfall in northern China but a lowered annual rainfall in southern China (e.g., Ding, 1994; Liu et al., 2014; Wang, Cheng et al., 2008; Zhou et al., 2011). This out-of-phase pattern with regard to northern China wet (dry) and southern China dry (wet) is known across a broad range of decadal, centennial, and millennial scales during the Holocene (e.g., Dallmeyer et al., 2013; Liu et al., 2015; Rao et al., 2016; Wang, Cheng et al., 2008; Zhou et al., 2009). The rainfall belt across monsoonal China takes place at the periphery area of southerly wind centers that are situated at the northwestern flank of West Pacific Subtropical High (WPSH), which shifts northward (southward) associated with the stronger (weaker) EASM circulation, finally resulting in an increased (reduced) precipitation in northern China but a reduced (increased) precipitation in southern China (e.g., Liu et al., 2015; Rao et al., 2016; Zhao & Zhou, 2009; Zhou et al., 2011). Consequently, a regional-scale record for annual precipitation in NC is imminently needed to estimate the overall EASM intensity within the context of Holocene monsoon studies over the entire East Asian continent.

Quantitative paleoclimatic data sets are also valuable for interpreting prehistoric population dynamics during the Holocene (e.g., An et al., 2005; Hou et al., 2016; Li et al., 2017). It has been widely confirmed that northern China has a long history of rain-fed agricultural development and persistent human settlement (e.g., Barton et al., 2009; Wang et al., 2015; Yu et al., 2012). Previous studies in different regions of NC have qualitatively discussed the possible connections between climatic shifts and demographic fluctuations in various aspects, suggesting that warm or humid climatic conditions were favorable to population expansion, whereas drought or cold intervals resulted in population decline (e.g., An et al., 2006; Pang & Huang, 2003; Yu et al., 2012), but it is worth noting that these conclusions are not unanimously accepted and therefore are still under debate (e.g., Buchanan et al., 2008; Li, An, et al., 2015; Shennan et al., 2013). However, until now, there has no attempt to numerically disentangle the individual effects of precipitation and temperature as well as their shared effects on independently accounting for the amount of variations in the increase and decline of Holocene population (HP) size at a large-scale in NC.

Zonal vegetation distribution in northern China is especially susceptive to small-scale precipitation variations, and it changes from humid and semihumid wooded forest to semiarid and arid grassland along a pronounced southeast-northwest precipitation gradient (e.g., Li, Xu, et al., 2015; Zhao et al., 2009). It has been demonstrated that annual mean precipitation (PANN) is the most important and ecologically meaningful climatic variable affecting surface pollen distributions in NC (e.g., Cao et al., 2014; Li, Xu, et al., 2015; Luo et al., 2010). During the last decade, fossil pollen assemblages have been employed as a reliable biological proxy for quantitative Holocene PANN estimations in northern China (e.g., Jiang et al., 2006; Stebich et al., 2015; Xu et al., 2010). Additionally, pollen data sets from lake deposits have been indicated to represent an overall signal of regional climate and vegetation, due to a blended process of pollen dispersal, deposition, and preservation within the entire catchments (e.g., Birks et al., 2010; Seppä et al., 2004; Xu et al., 2016). This makes it possible to synthesize a set of pollen-based PANN reconstructions spanning the Holocene at a subcontinental scale solely for northern China.

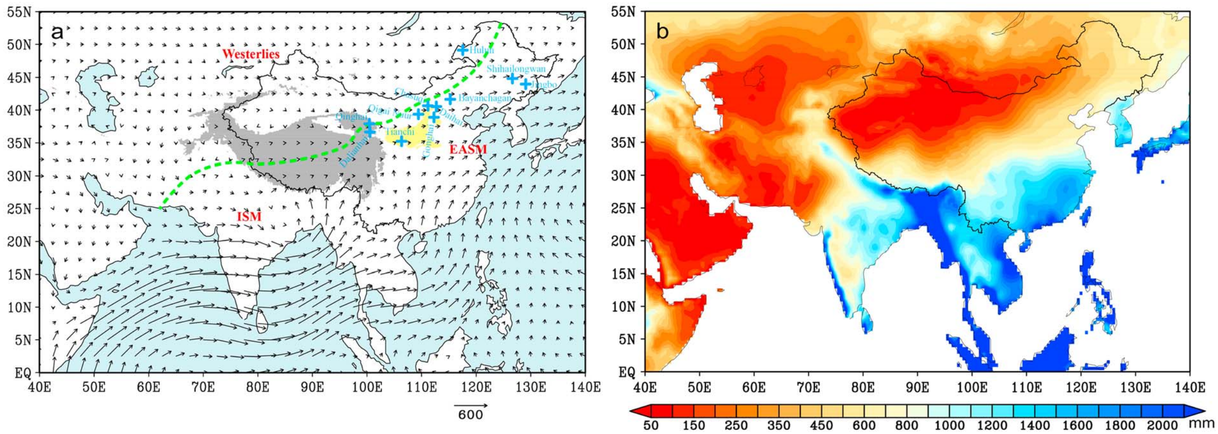

Figure 1. (a) Averaged summertime flux vectors (kg · m^{-1} · s^{-1}) for water vapor transportation from surface to 300 hPa between June and August from the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalyzed data (Kalnay et al., 1996) for the interval of 1971–2000. Localities of Holocene fossil sites shown as crosses from northern monsoonal China (see Table S1 for details). EASM, ISM, and Westerlies indicate eastern Asian summer monsoon, Indian summer monsoon, and westerlies, respectively. (b) Annual mean precipitation (PANN) of China obtained from the Climate Research Unit (CRU) data set (New et al., 2002). The green dashed line denotes the northern boundary of modern summer monsoon (Chen et al., 2008).

In the current study, we take advantage of pollen data to produce new PANN inferences and combine earlier pollen-derived PANN series, so as to contribute a geographically coherent record for Holocene PANN anomaly, for the first time, as a representative for the whole region of northern China. We then compare our PANN record with existing regional-scale numerical Holocene temperature and population reconstructions in NC, in order to quantitatively distinguish the independent role of precipitation and temperature in influencing the long-term prehistoric demographic fluctuations in northern China.

2. Data and Methods

2.1. Study Region and Data Quality Assessment

The northern section of monsoonal China considered in this study encompasses the North China Plain, northeastern China, central and eastern Inner Mongolia, Loess Plateau, and northeastern Tibetan Plateau (Figure 1a). The study area spans a wide range of latitudes and longitudes, with elevations above sea level ranging from lower than 600 m in the east to higher than 3,000 m in the west. In line with the continental precipitation gradient (Figure 1b), modern vegetation zones vary southwestwardly from cold coniferous forest and warm temperate deciduous forest to semiarid steppe and high-cold alpine meadow (e.g., Hou, 2001; Li, Xu, et al., 2015). Rainfall occurs mainly from June to August, and summer monsoon accounts for greater than 80% of the total annual precipitation (e.g., Domrös & Peng, 1988).

Several high-resolution pollen records covering the Holocene have been published in different territories of NC (e.g., Stebich et al., 2015; Sun & Feng, 2013; Xu et al., 2010). Here two pollen sites were utilized to obtain new Holocene PANN records (Table S1 in the supporting information): Chasuqi record was taken from the East Asia Quaternary Pollen Database (EAQPD) consisting of 271 fossil records that have been lately set up by Cao et al. (2013); and Jingbo record was contributed by Chen, Shen, et al., 2015). Nineteen published Holocene PANN sequences at nine fossil sites were obtained from the original publications (Table S1). The reason to reconstruct PANN for NC is that it has been revealed to be the most important climatic parameter for regional-scale pollen distribution and that it has been used as the most common climatic variable reconstructed from fossil pollen data sets (e.g., Cao et al., 2014; Li, Xu, et al., 2015; Luo et al., 2010). To best guarantee reliability of the regionally synthesized record in NC, all PANN sequences were critically selected conforming to rigorous standards listed as follows: (i) solely from lake sediment cores, (ii) under the strong influence of EASM, (iii) reliable chronology with a minimum of seven dates (except for Chasuqi with four dates), (iv) high temporal resolution lower than 90-year between samples (except for Bayanchagan with a 130-year resolution), (v) continuous records covering the Holocene with no evident sedimentary hiatuses, and (vi) relatively low human impact within a drainage basin of each lake (Table S1). These criteria have been broadly employed for data scrutiny and site selection when reliably performing large-scale proxy-based

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Holocene climatic syntheses worldwide (e.g., Chen et al., 2008; Wanner et al., 2008; Zhao et al., 2009). To obtain a consistent geochronology, all published chronological data sets from the sites were based on radiocarbon methods. Radiocarbon ages were transferred to calendar years before present (cal. yr BP) based on the IntCal13 calibration database (Reimer et al., 2013). Age-depth models were taken from the original publications or estimated with the CLAM package (Blaauw, 2010) in R (R Development Core Team, 2012).

2.2. Data Treatment

Weighted averaging-partial least squares (WA-PLS) regression and calibration model (ter Braak & Juggins, 1993) based on the Chinese modern pollen-climate database (Zheng et al., 2014) was used to obtain new PANN reconstructions. This method has been demonstrated to perform better in comparison with other calibration methods when using pollen data sets for inferring Holocene climatic variability in China as well as other areas in Eurasia (e.g., Birks et al., 2010; Li, Zhao, et al., 2014; Seppä et al., 2009; Xu et al., 2010). Reconstructive capacity of the WA-PLS model was tested to be robust after carrying out leave-one-out cross-validation (Li et al., 2017). Statistical outputs indicative of the WA-PLS model performance were presented in detail by Li et al. (2017). All terrestrial pollen taxa were taken into account for the PANN estimates, and their percentage values were square-root transformed to reduce the noise and overall variance (Prentice, 1980). The number of terrestrial pollen taxa in Chasuqi and Jingbo is 37 and 52, respectively (Cao et al., 2013; Chen, Shen, et al., 2015). The two new PANN reconstructions were conducted by utilizing the R package RIOJA (Juggins, 2012).

In order to integrate a large amount of quantitative data values from all sites, each of the 21 Holocene PANN estimates was first calculated as standard anomalies (or departures) from the modern observed PANN values at the corresponding site. The arithmetical procedure regarding site composite record was then utilized to compile and summarize all values of the standardized PANN anomalies with predicted error bars in a concise and consistent format for easier computation and reporting (e.g., Chen et al., 2008; Zhang et al., 2011). Such a synthesizing methodology has been successfully applied to yield an array of regional-scale Holocene moisture evolutions in different parts of China (e.g., Ran & Feng, 2013; Zhao et al., 2009). As recommended by earlier studies, the individual PANN series were also normalized with a 200-year interval and were hence averaged to one composite sequence within the binned time window according to the unified chronological order. In this manner, an absolutely quantified, regional-scale Holocene PANN anomaly (200-year resolution) relative to a baseline of the modern-day values was finally produced for northern China.

To examine the numerical relationships between climatic (precipitation and temperature) changes and prehistoric population dynamics in northern China, variation partitioning (Borcard et al., 1992), redundancy analysis (RDA; ter Braak & Smilauer, 2002), and correlation analysis were adopted. The variation partitioning approach is able to objectively decompose the total variation of paleoecological data sets into independent components reflecting the variation explained by a single climatic variable, joint effects of two or more variables, and the fraction of variation that is not explained by the used variables (e.g., Borcard et al., 1992; Reitalu et al., 2013). In comparison with the PANN record provided in this study, a regional-scale Holocene anomaly record (200-year resolution) for annual mean temperature (TANN) in NC was contributed by Hou and Fang (2012). HP size data sets were extracted from published studies that estimated the summed probability distribution of extensive archeological radiocarbon dates as an effective proxy to reveal prehistoric demographic trends in NC (800-year resolution; Wang et al., 2015) and Chinese Loess Plateau (CLP; 200-year resolution; Li, An, et al., 2015). Using frequency distributions of archeological radiocarbon ages as a reliable indicator of prehistoric demography has been based on the widely approved assumption that more population would lead to more production or deposition of cultural carbon, thereby offering more determinations (e.g., Anderson et al., 2011; Peros et al., 2010). This approach has been broadly applied to reconstruct large-scale past demographic changes in different regions of the world (e.g., Kelly et al., 2013; Munoz et al., 2010; Williams et al., 2008). To quantitatively compare different records, the HP record in NC was interpolated to have a 200-year resolution, which is same to the temporal resolution of the PANN, TANN, or HP record in CLP. RDA was carried out to evaluate statistical associations among the records of PANN, TANN, and HP in both NC and CLP. Monte Carlo permutation tests were run with 999 permutations to evaluate the statistical significance of PANN and TANN. All analyses were performed with the R package VEGAN (Oksanen et al., 2013). Furthermore, correlation coefficients were calculated between different Holocene climatic and population sequences in this study. In all statistical analyses of this study, all of the four records have a 200-year

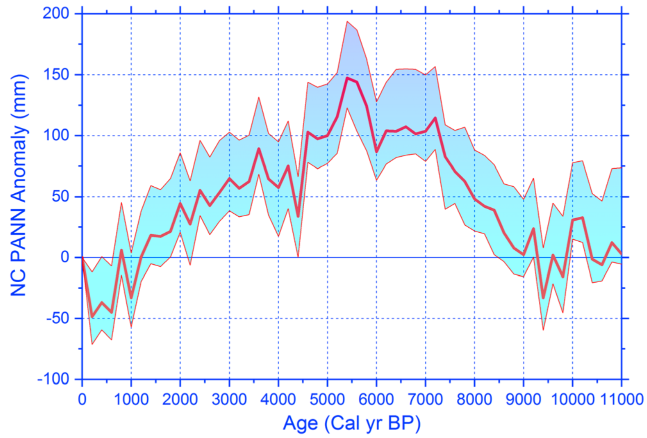

Figure 2. The regionally synthesized PANN record with standardized error bars for northern China over the last 11,000 years.

resolution; each of the three records (PANN, TANN, and HP in NC) individually has 56 data points; only one record (HP in CLP) has 43 data points; and the original uninterpolated record (800-year resolution) of HP in NC has 14 data points.

3. Results and Discussion

In general, the PANN anomaly displays a three-part division of Holocene precipitation course at a regional scale in NC: a marked wetting of the early-Holocene between 11,000 and 7,800 cal. yr BP, a moistest interval of the mid-Holocene from 7,800 to 3,400 cal. yr BP in which PANN was about 50–100 mm higher than at present, and a stepwise drying of the late-Holocene after 3,400 cal. yr BP (Figure 2 and Table S2 in the supporting information). The reliability of our Holocene PANN reconstruction can be validated by comparison with other Holocene hydrological records in NC. For example, large-scale frequency analyses indicate that a prominent Holocene soil development took place between 8,600 and 3,200 cal. yr BP in CLP (Figure 3b), suggesting a strong pedogenesis process associated with a maximum rainfall (Wang et al., 2014). Correspondingly, this is in tune with a minimum occurrence of loess or eolian-sand deposition during the mid-Holocene (Figure 3c) in the area of summer monsoonal border in NC (Li, Wu, et al., 2014). Similarly, magnetic susceptibility records that are widely regarded as a direct proxy for precipitation from loess-soil sections on the CLP, such as the Yaoxian and Yulin profiles (Figures 3d and 3e), reveal a highest degree of precipitation occurring from 8,000 to 4,000 cal. yr BP (Lu et al., 2013; Xia et al., 2014). A regional-scale climate modeling study also demonstrates that NC was characterized by a more humid climate in the mid-Holocene (Jin et al., 2013). In summary, all of these Holocene records embracing an immense geographical area, coherently exhibit a mid-Holocene maximum of moisture or precipitation in northern China.

Notably, orbital-scale summer insolation has been traditionally to be interpreted as the dominant force driving the Holocene evolution of monsoon precipitation (e.g., Dykoski et al., 2005; Thomas et al., 2016;

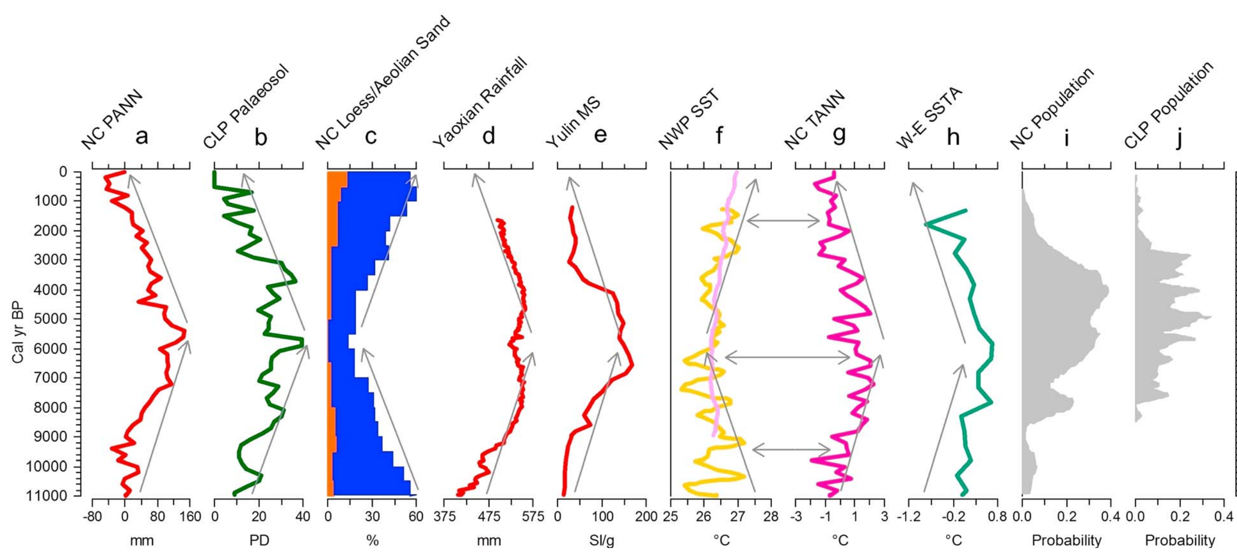

Figure 3. Comparison of (a) regionally compiled PANN record for northern China (NC) with other related Holocene records: (b) probability density of paleosol distribution in Chinese Loess Plateau (CLP; Wang et al., 2014); (c) frequency distribution of loess and eolian sand deposition in NC (Li, Wu, et al., 2014); (d) estimated rainfall at the Yaoxian loess-paleosol section in CLP (Xia et al., 2014); (e) magnetic susceptibility record from the Yulin loess-paleosol section in CLP (Lu et al., 2013); (f) sea surface temperature records in northwestern Pacific (NWP) based on the Mg/Ca data of marine core A7 (yellow line; Sun et al., 2005) and the Kiel climate model simulation (green line; Zhang et al., 2017); (g) regional-scale anomaly record for annual mean temperature in NC (Hou & Fang, 2012); (h) thermal gradient of sea surface temperature anomaly between the west and east equatorial Pacific (Koutavas & Joanides, 2012); and estimated population size in (i) NC (Wang et al., 2014) and (j) CLP (Li, An, et al., 2015) during the Holocene.

Wang, Wu et al., 2008). However, our PANN record reveals that the Holocene peak interval of precipitation in NC lagged about 4,000 years in timing compared with that of the solar insolation. It is therefore likely that apart from the solar forcing alone, there exist other internal forcing mechanisms affecting the Holocene precipitation dynamics in NC. In essential, the EASM system is a result of strong pressure gradient between East Asian continent and Northwest Pacific Ocean, as determined primarily by striking thermal contrast between warmed landmass and cooled ocean during the monsoon season (e.g., Maher & Hu, 2006; Zhou & Zou, 2010; Zhou et al., 2011). Quantitative proxy-based reconstructions and model simulations of sea surface temperatures in northwestern Pacific, such as the Mg/Ca-based record from a marine core (Sun et al., 2005) and the Kiel Climate Model simulated results (Zhang et al., 2017), show a coolest mid-Holocene, but a warming early- or late-Holocene (Figure 3f), albeit with some possible uncertainties. However, this pattern is inversely correlated with the temperature anomaly record in northern China (Hou & Fang, 2012), which indicates a warmest mid-Holocene, but a cooling early- or late-Holocene (Figure 3g). Consequently, the zonal land-ocean thermal contrast was particularly larger during the mid-Holocene, but relatively smaller during the early- or late-Holocene (Figure 3). This would have resulted in a strengthened low-pressure system across East Asia, as well as an intensified WPSH with its overall position shifting northward in the mid-Holocene. Such a causal relation can be supported by a short-term reconstruction of the Asian-Pacific Oscillation over the last millennium (Zhou et al., 2009). Accordingly, stronger southerly winds associated with the intensified WPSH would carry more water vapor from northwestern Pacific to northern monsoonal China, thereby leading to more precipitation in NC during the mid-Holocene.

Furthermore, the strength and location of WPSH are also affected by the thermal contrast between western and eastern equatorial Pacific Ocean (e.g., Rao et al., 2016; Tan, 2011). The increase of west-east temperature gradient over equatorial Pacific tends to form a La Niña-like status, possibly causing the northward extension of WPSH; however, the decrease of west-east Pacific temperature gradient coincides with an El Niño-like status, as well as the southward movement of WPSH (e.g., Chang et al., 2000; Zhao et al., 2010). The integrated sea surface temperaturerecords based on many marine sediment cores from both western and eastern tropical Pacific (Koutavas & Joanides, 2012) display an augmented west-east thermal contrast in the mid-Holocene, whereas a significantly reduced thermal contrast in the early- or late-Holocene (Figure 3h). This trend is positively correlated with the reconstructed PANN record in this study. Given that the monsoon rain belt is mainly located in the north side of WPSH, the maximum west-east thermal contrast spanning the entire equatorial Pacific during the mid-Holocene would have clearly reinforced the intensity of WPSH and its further northward advancement, therefore bringing more precipitation to northern China in the same period.

The variation partitioning analysis quantitatively shows that PANN alone explains a much higher proportion (43%) than TANN (3.2%) and their shared effects (0.8%) in independently accounting for the total variation of long-term Holocene demographic trends in both NC and CLP (Figure S1 in the supporting information). This is also supported by results of the RDA and correlation analyses, indicating that PANN is strongly correlated with the estimated HP in NC ($r = 0.737$ [or 0.753]; $p = 0.003$ [or < 0.001]; $n = 14$ [or 56]) and CLP ($r = 0.659$; $p = 1.533$; $n = 43$), but TANN is weakly correlated with the HP in NC ($r = 0.051$ [or 0.291]; $p = 0.862$ [or 0.029]; $n = 14$ [or 56]) and CLP ($r = 0.235$; $p = 0.129$; $n = 43$; Figure S2 and Table S3 in the supporting information). It is notable that the results of statistical analyses for the period from 11,000 to 8400 cal. yr BP should be treated with caution, because there was less number of data points in the HP record of CLP in comparison with the other three records during this interval (Figure 3). Given that CLP is a part of NC, all statistical analyses including the variables of PANN, TANN, and HP in NC may roughly reflect the overall relationship between climatic change and human population in northern China as a whole during the Holocene. As shown in Figure 3, prehistoric human population obtained its highest extent at circa 6,000–3,000 cal. yr BP in both NC and CLP, coinciding closely with the maximum degree of positive PANN anomalies in this interval. However, overall TANN values in NC reached to their maxima at 9,000–6,000 cal. yr BP, corresponding to comparatively lower PANN as well as population (Figure 3). Of special note, between 7,400 and 6,000 cal. yr BP, both precipitation and rainfall appeared to be high, but human population was relatively lower and did not immediately increase, indicating that human occupation might take time to respond to precipitation changes. The possible reason is that this interval was identified as a transitional period for human subsistence strategy altering from hunter-gatherer economy to millet-based agriculture in NC, with fairly lower food productivity incapable of feeding a large human population (e.g., Barton et al., 2009; Li, An, et al., 2015;

Zhao, 2011). Subsequently, the permanent and intensive agriculture was well established in NC during about 6,000–3,000 cal. yr BP, as clearly evidenced by the most significant increases in sites of crop seeds, storage and agricultural tools, and introduction and spread of foxtail millet, wheat, and rice cultivations (e.g., Fuller et al., 2009; Li et al., 2007; Lu et al., 2009; Ruddiman et al., 2008; Yu et al., 2012). As a result, the internal factors in regard to social and agricultural developments facilitated the greatest population expansion at circa 6,000–3,000 cal. yr BP in NC. As for the external factors with respect to significant climatic influence, this prosperous peopling can be attributed mainly to a maximal water supply vitally important for dryland farming with sufficient PANN about 75–150 mm higher than at present and to a lesser extent a relatively warm climate with TANN about 0–2 °C higher relative to the present, thus all together providing a favorable condition for substantial crop yield and rapid population increase across northern China.

4. Conclusions

In this study, we contribute the first systematically compiled anomaly record for the Holocene precipitation relative to the modern-day values covering the northern domain of monsoonal China, based on an extensive network of 21 pollen-inferred PANN reconstructions. The regionally synthesized record in NC illustrates that PANN increased by approximately 50 mm between 11,000 and 7,800 cal. yr BP, acquired the maximum values from 7,800 to 3,400 cal. yr BP in which PANN was about 50–100 mm higher than at present, and decreased to the modern degrees after 3,400 cal. yr BP.

The pollen-based Holocene PANN sequence has been demonstrated to be robust and reliable as a representative for NC by an extensive comparison with other proxy-based independent or synthesized records with regard to the Holocene moisture changes from the same geographical region. The marked precipitation variations in NC during the Holocene may be essentially linked to the changing zonal thermal contrasts of land-ocean and west-east equatorial Pacific, likely affecting the strength and location of WPSH that might primarily modulate the EASM intensity as well as the monsoonal rainfall extent in northern China.

The variation partitioning analysis first reveals that at a large-scale PANN may be more important than TANN in independently accounting for the general variation of HP fluctuations in northern China. It is noteworthy that more regional-scale quantitative proxy-based reconstructions or transient model simulations are needed to evaluate the Holocene precipitation anomalies in other regions of China and to further test the relative importance of numerical paleoclimatic variations on the long-term demographic changes at different spatial-temporal scales.

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